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Magnetron and Travelling Wave Tube

Magnetron. Magnetron forms one of the various high power microwave oscillator and it forms the basis of many a microwave radar transmitter system even nowadays. This microwave generator makes use of magnetic field for producing oscillations at microwave frequencies. Microwave magnetrons now find many applications apart from radar. They are capable of furnishing megawatts of peak power in the centimetre wavelength range and may be operated at wavelengths extending down to millimetre range.

All magnetrons consist of some form of anode and cathode operated in a magnetic field that is normal to the electric field between the cathode and the anode. The magnetic field causes electrons emitted from the cathode to move in curved paths. In case the flux density of the magnetic field is sufficiently great, the electrons do not strike the anode but return to the cathode and the anode current is cut off

Magnetrons form three categories namely

(*a*) Negative resistance magnetrons.

(*b*) Cyclotron frequency magnetrons.

(*c*) Travelling wave magnetrons.

Negative resistance magnetrons make use of a static negative resistance present between two anode electrodes/ plates. Cyclotron frequency magnetrons depend on synchronism between an alter

nating component of electric field and periodic oscillation of electrons in a direction parallel to this electric field. The third type, *i.e.* travelling wave magnetrons depend on interaction of moving electrons with a travelling electro-magnetic field travelling with a constant angular or linear velocity. The frequency of operation for Negative Resistance Magnetrons ranges upto 500 MC. The frequency range for cyclotron frequency magnetrons and travelling wave magnetrons falls beyond 100 MC. Must modern magnetrons come under the category of travelling wave magnetrons.

Constructional features of a cavity magnetron. The cavity magnetron or simply a magnetron is simply a diode usually

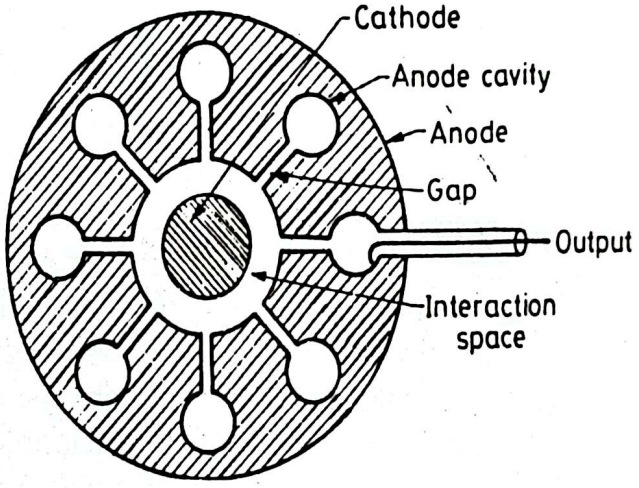

Fig. 8.1. Cross-section of hole and slot magnetron (top view).

of cylindrical construction employing a radial electric field, an axial magnetic field and an anode structure with permanent cavities. Fig. 8.1 shows the cross-section of a HOLE-AND-SLOT magnetron, here the cylindrical cathode is surrounded by the anode with cavities and thus a radial d.c. electric field will exist. The magnetic field due to a horse-shoe type of magnets used in conjunction having the magnetron produces axial magnetic field, *i.e.* has lines of force (magnetic) passing through the cathode and the surrounding interaction space ; therefore, the lines are at right angles to the structure cross-section of Fig. 8.1. The magnetic field is also d.c. and since it is perpendicular to the plane of the radial electric field, the magnetron is referred to as a *Crossed Field* device.

The output of the magnetron is taken from one of the cavities, by means of a co-axial line as is clear from Fig. 8.1 or through a

waveguide depending on the power and frequency. It is to be noted that the output coupling loop leads to a cavity resonator to which a waveguide is connected and thus the whole output from this magnetron is taken *via* a waveguide. The material used for the anode is normally copper regardless of its shape.

There are a number of resonant cavities in a magnetron and, therefore, it must have an equal number of resonant frequencies and/or modes of oscillation. The mode that is used must be self-consistent; for example it is not possible for an 8 cavity magnetron (the most practical type) to employ a mode in which phase difference between adjacent anodes is 30° ; this leads to a total phase difference of $30 \times 8 = 240°$; meaning thereby that first anode pole piece is out of phase from itself by 120°. It can be seen that the smallest phase difference between two adjacent pole pieces obtainable with an 8 cavity magnetron is 45° or $\pi/4$ which results in an overall phase shift of 360° or 2π radians which is self-consistent as is required. This $\pi/4$ mode is seldom used in practice because is does not give suitable characteristics and the more normally used is the π mode. Details about π mode will be dealt within the following discussion.

Now we proceed to derive a mathematical relationship which gives the value of critical magnetic field density required by the electron to just graze the anode.

Two types of magnetron are used from construction point of view :

(*a*) Parallel plate magnetron

(*b*) Cylindrical magnetron.

Parallel plate magnetron. Fig. 8.2 shows a simple diagram used to calculate the value of the cut off magnetic field strength required by an electron to just graze the anode.

Let V_0 be the voltage applied between anode and the cathode of a parallel plate magnetron. An electron leaving the cathode is under influence of an electric field as well as a magnetic field which acts into the plane of the paper and perpendicular to it.

Electric field strength between the plates,

$$W = \frac{V_0}{d} \qquad ...(8.1)$$

Force on an electron in a magnetic field,

$$F = Qv\,B \sin\theta \qquad ...(8.2)$$

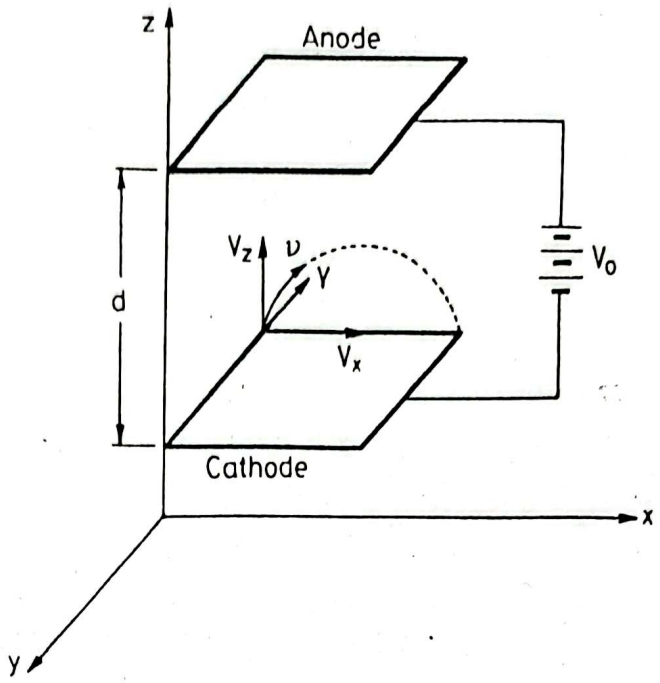

Fig. 8.2.

where θ is the angle made by the magnetic field with the direction of electric field.

If $\theta = 90^\circ$

then $F = QvB$ ...(8.2*a*)

and the path traced by an electron is a circle. In Eq. (8.2),

Q = charge on electron

v = velocity with which electron moves

B = Magnetic flux density.

Now the force acting on the electron given by Eq. (8.2) is equivalent to a centrifugal force exerted due to motion of electron in a circular path of radius r and is given by Eq. (8.3) as follows :

i.e. we have $$f = \frac{mv^2}{r} = QvB \qquad ...(8.3)$$

so that $$r = \frac{m}{Q}\frac{v}{B} = \frac{m}{e}\frac{v}{B} \qquad ...(8.4)$$

where $Q = e$ = Electronic charge

and r = radius of circle in which the electron moves.

Angular velocity of electron is given as

$$\omega_e = \frac{v}{r} = \frac{eB}{m} \qquad ...(8.5)$$

Vectorially, the force on electron is given as

$$\bar{f} = e\,(\bar{v} \times \bar{B} + \bar{E})$$

where v, B, E are velocity vector, magnetic field strength vector and electric field vector respectively, hence magnitude of the force f_z along Z-direction is

$$f_z = m.a_z = -e[E + v_x \,.\, B] \qquad ...(8.6)$$

and force (magnitude) along X direction is

$$f_x = m.a_x = +ev_zB \qquad ...(8.7)$$

In above equations a_x and a_z are values of acceleration in X and Z directions respectively.

Eqs. (8.6) and (8.7) may be rewritten as

$$\frac{dv_x}{dt} = \frac{eB}{m} v_z = w_e v_z \qquad ...(8.7a)$$

where $$w_e = \frac{eB}{m} \qquad ...(8.7b)$$

and $$\frac{dv}{dt} = -\frac{eE}{m} - \frac{eB}{m} v_x$$

$$= -w_e v_x + \frac{eV_0}{md} \qquad ...(8.6a)$$

($\because$ $E = -\frac{V_0}{d}$, where V_0 is the voltage applied between two parallel plates)

Differentiation of Eq. (8.6a) yields

$$\frac{d^2v_z}{dt^2} = -w_e \frac{dv_x}{dt}$$

$$= -w_e^2 v_z \qquad ...(8.8)$$

Eq. (8.8) is a differential equation of second degree and its most general solution may be written as

$$v_z = c_1 \sin \omega_e t + c_2 \cos \omega_e t \qquad ...(8.9)$$

Now at $t = 0,\ v_z = 0 \Rightarrow c_2 = 0$

$\therefore$ $$v_z = c_1 \sin \omega_e t \qquad ...(8.10)$$

Differentiating (8.10) w.r.t. t, we get

$$\frac{dv_z}{dt} = c_1\omega_e \cos \omega_e t \qquad ...(8.11)$$

Equating Eqs. (8.11) and (8.6a) we obtain

$$c_1\omega_e \cos \omega_e t = -\omega_e v_x + \frac{eV_0}{m.d}$$

At $t = 0, v_x = 0$

$$\Rightarrow c_1 \omega_e = \frac{eV_0}{md}$$

or
$$c_1 = \frac{eV_0}{md\omega_e} \quad ...(8.12)$$

So that the solution of (8.9) is obtained as

$$\boxed{v_z = \frac{eV_0}{md\omega_e} \sin \omega_e t} \quad ...(8.13)$$

From Eq. (8.6*a*), we get

$$v_x = \frac{eV_0}{\omega_e md} - \frac{1}{\omega_e} \cdot \frac{dv_z}{dt}$$

$$= \frac{eV_0}{\omega_e md} [1 - \cos \omega_e t] \quad ...(8.14)$$

Eq. (8.14) is obtained by differentiating Eq. (8.13) and rewriting it in above equation

i.e.
$$\frac{dv_z}{dt} = \frac{eV_0}{md\omega_e} \omega_e \cos \omega_e t$$

$$\Rightarrow \frac{1}{\omega_e} \frac{dv_z}{dt} = \cos \omega_e t \left[\because \frac{eV_0}{md} = \frac{eE}{m} = \omega_e \right]$$

Now Eq. (8.13) can be reproduced here as

$$v_z = \frac{dz}{dt} = \frac{eV_0}{md\omega_e} \sin \omega_e t \quad ...(8.14a)$$

Integrating Eq. (8.13) w.r.t. t gives us

$$z = -\frac{eV_0}{md\omega_e^2} \cos \omega_e t + C \quad ...(8.15)$$

At $t = 0, z = 0$

$$\Rightarrow C = \frac{eV_0}{\omega_e^2 md}$$

$$\therefore \quad z = \frac{eV_0}{md\,\omega_e^2} [1 - \cos \omega_e t] \quad ...(8.16)$$

Similarly from Eq. (8.14), we have

$$v_x = \frac{dx}{dt} = \frac{eV_0}{\omega_e md} (1 - \cos \omega_e t)$$

Differentiating, (8.14) w.r.t. t we get

$$x = \frac{eV_0}{\omega_e md} t - \frac{eV_0}{md\omega_e^2} \sin \omega_e t + C' \quad ...(8.17)$$

And at $t = 0, x = 0 \Rightarrow C = 0$

so that $$x = \frac{eV_0}{\omega_e md}\left[t - \frac{\sin \omega_e t}{\omega_e}\right] \quad ...(8.18)$$

Eq. (8.16) could be rewritten here

$$z = \frac{eV_0}{m\omega_e^2 d}(1 - \cos \omega_e t) \quad ...(8.16)$$

Now for value of z to be maximum, we have

$$\cos \omega_e t = -1 \Rightarrow \omega_e t = \pi$$

$$\therefore \quad z_{max} = \frac{2eV_0}{m\omega_e^2 d} = \frac{2eV_0/d}{m.\left(\frac{eB}{m}\right)^2}$$

or $$z_{max} = 2\frac{m}{e}\frac{V_0}{d}\cdot\frac{1}{B^2} \quad ...(8.19)$$

At $d = z_{max.}$, the electron just grazes off the parallel plate so that we have the expression for cutoff value of magnetic field, B_c as

$$\boxed{B_c = \sqrt{\frac{2mV_0}{ed^2}}} \quad ...(8.20)$$

Eq. (8.20) is an expression for cutoff magnetic field in case of *Parallel plate magnetron.*

Now we proceed on to derive an expression for cut off magnetic field for a cylindrical magnetron.

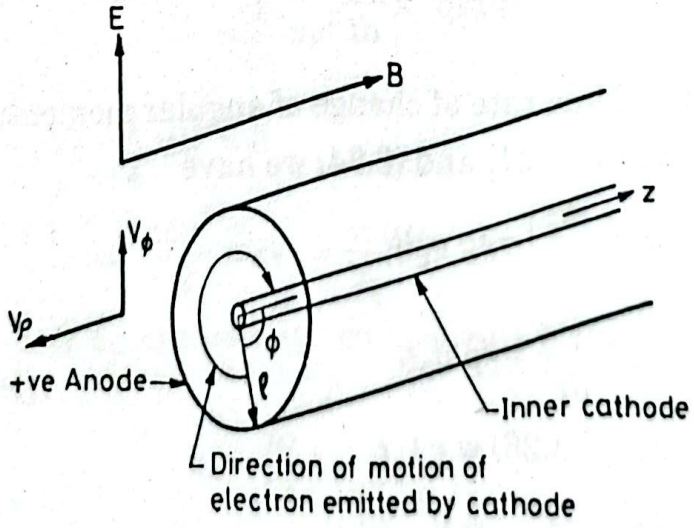

Fig. 8.3. Cylindrical magnetron.

Cylindrical magnetron. A cylindrical magnetron consists of two cylindrical electrodes—the inner one being the negative cathode and the outer one being the **anode.**

are small and large in number to ensure that a suitable RF fields is maintained in the interaction space. Due to this even strapping may not be effective in achieving the complete separation of modes.

Another efficient method consists in having an anode block with a pair cavity systems of very dissimilar shape, and resonant frequency. Such a rising sun structure is shown in Fig. 8.8 and it has the effect of separating the π mode frequency from the others so that the magnetron is not likely to oscillate at any of the other modes because the d.c. fields would not support them. Also no strapping is required with the rising sun magnetron.

Frequency Pushing and Pulling. Just as in Reflex klystron, it is possible to change the resonant frequency of magnetron by changing the anode voltage. This frequency pushing, as it is called, is due to the fact that the change in anode voltage results in a change a orbital velocity of electrons. This alters the rate at which the energy is given up to anode resonators and, thus, changes the oscillating frequency.

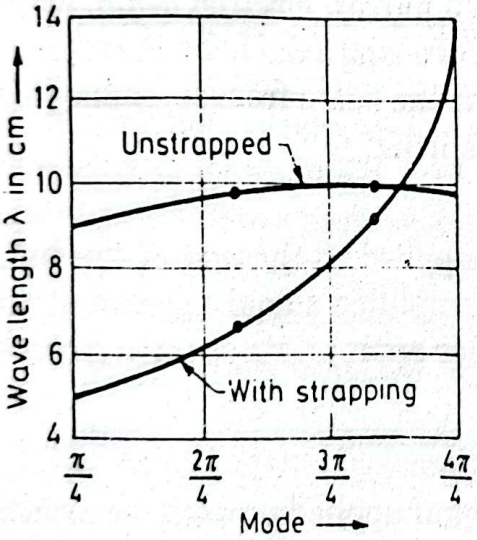

Fig. 8.7.

Also, magnetron is susceptible to frequency variations due to changes of load impedances. This takes place regardless of whether these load variations are purely resistive or involve reactive load variations but is more severe in case of reactive variations. These frequency variation is known as frequency pulling and is caused by variations in load impedance reflected into cavity resonators. This must be prevented because the magnetron is a high power oscillator unlike most other oscillators.

Performance characteristics of a magnetron are studied on a *Rieke Diagram* (out of scope of this book).

Travelling Wave Tube. The travelling wave tube is an amplifier which makes use of a distributed interaction between an electron beam and a travelling wave. To prolong the interaction between an electron beam and an RF field, it is necessary to ensure that they are both travelling in the same direction with nearly the same velocity. It differs from the multicavity klystron, in which the electron beam travels but the RF field remains stationary. The

electron beam travels with a velocity governed by the anode voltage, which for a typical value of anode voltage can be as high as 0.1 v_c, where v_c is the velocity of light in vacuum. The RF field propagates with a velocity equal to velocity of light v_c. The interaction between RF field and moving electrons will take place only when the velocity of RF field is retarded by some means. The slow-wave structures to retard RF field, either use a helix or a waveguide arrangement.

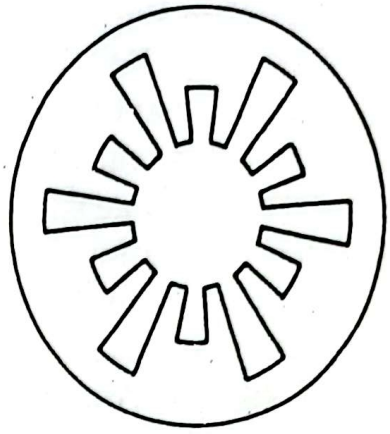

Fig. 8.8. Rising magnetron anode block.

The physical construction of a typical travelling wave tube using a helix is shown in Fig. 8.9. It has an electron gun, as used in klystrons, which is used to produce a narrow electron beam, which in turn is passed through the centre of a long axial helix. A magnetic focusing field is provided, to prevent the beam from spreading and to guide it through the centre of the helix.

The signal to be amplified to applied to the end of the helix adjacent to the electron gun. The amplified signal appears at the output or other end of the helix under appropriate operating conditions.

Description. When the RF signal applied propagates around the turns of the helix, it produces an electric field at the centre of the helix. The RF field propagates with a velocity of light, the axial electric field due to RF signal advances with a velocity of light multiplied by the ratio of helix pitch to helix circumference. So when the velocity of the electron beam travelling through the helix approximates the rate of advance of the axial field then, interaction takes place between them, which is of such a nature that on an average the electrons deliver energy to the wave on the helix. Thus the signal wave grows and amplified output is obtained. The travelling wave tube may be thought of as the limiting case of the multicavity klystron, which has a very large number of closely spaced gaps with a phase change that progresses from left to right at approximately the same velocity as the beam.

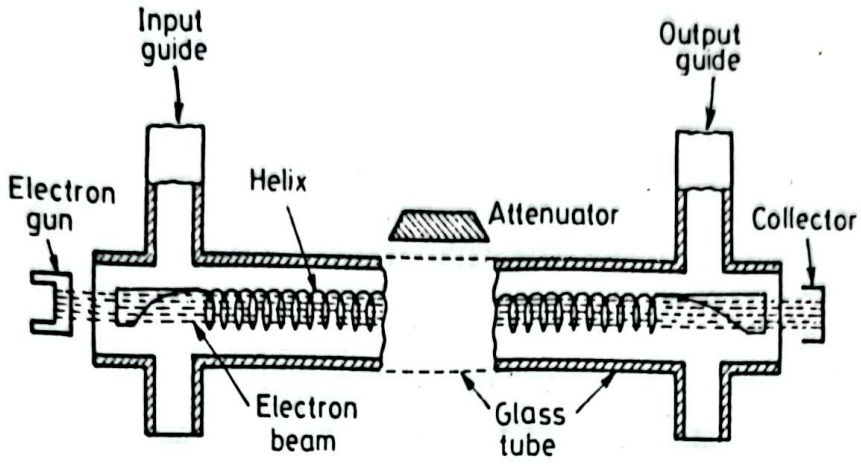

Fig. 8.9. Helix type travelling wave tube.

Although the process is more complex than the klystron, never the less, bunching takes place in the travelling wave tube. The mechanism of energy conversion by which electrons deliver energy to the signal can be understood by reference to Fig. 8.10. Fig. 8.10 (*a*) shows the distribution of electric field strength along the helix axis produced by the signal in absence of an electron beam. When axial electric field is zero, the electron *e* is unaffected by the signal on the helix as shown in Fig. 8.10. The electron e_1 is just to the left of *e*, so it encounters a positive axial electric field and is accelerated so that it tends to catch up with electron *e*. But electron e_2 encounters a decelerating field, so it slows down and thus e_1 tends to overtakes. So all the electrons centred about *e* are velocity modulated.

If the velocity of the electrons beam is same as that of RF signal than the electron *e* will be located at the zero of the solid wave as shown in Fig. 8.10 (2). As the electrons such as e_1 are to the left of the electron *e* these are accelerated, and so absorbs energy from the wave on the wire, weakening it to the left of *e*. Similarly electrons such as e_2, which are to the right of *e* are decelerated, and deliver energy to the wave, so increasing the wave amplitude to the right of *e*. Thus the bunch of electrons centred on *e* induces a second wave on the helix which produces an axial electric field that lags the solid wave by a quarter wavelength as shown.

Therefore bunching continues to take place, and the electrons in the bunch encounter retarding field and as a result deliver energy to the wave on the helix. The output thus becomes larger than the input, and amplification results. Although the amplitude of the induced wave increased but phase shift of the resultant wave

relative to the electron is also increased due to the fact that induced wave is larger.

Attenuator. To suppress the oscillations from being spontaneously generated in a travelling wave tube, it is necessary to prevent internal feedback arising from reflections due to impedance mismatch.

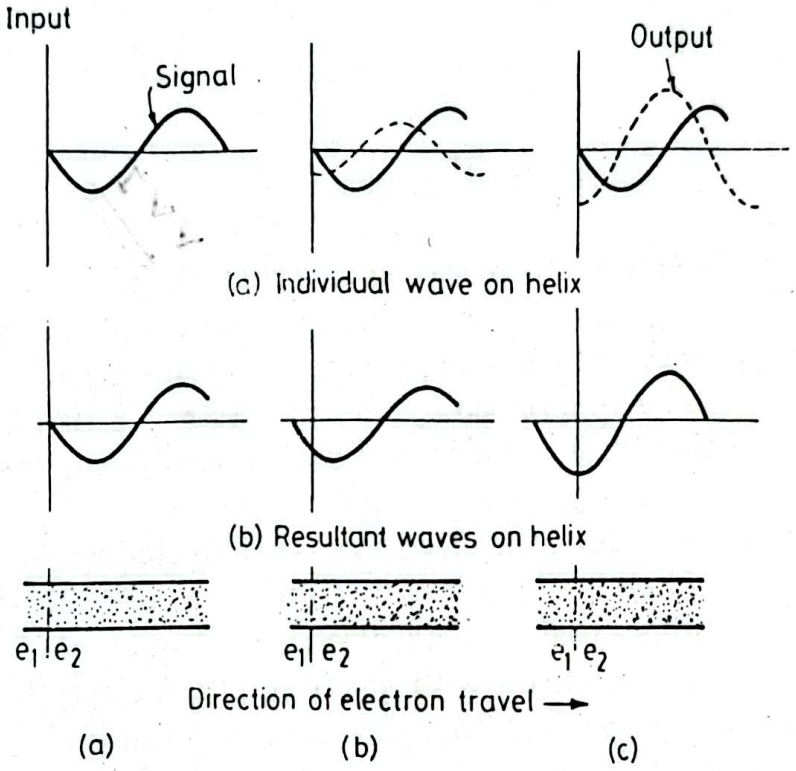

Fig. 8.10. Shows the mechanism of electrons bunching in a travelling wave tube.

Spurious signals are formed, because the energy is reflected back from the output terminals which travel towards gun end and are amplified along with the desired signal.

The problem can be solved by placing an attenuator in some convenient place in the tube. The glass wall of the tube is coated with aquadag, acts as an attenuator. The attenuator absorbs the spurious signal and to some extend absorbs growing signal in the helix. When the attenuator is placed near the input end of the tube, the bunching of the electrons remains unaffected. The reason of keeping attenuator at the input end of the tube is that the at-